NOTE.—The accompanying map is made from compass bearings, and distances measured by the time of marching.

Kambwire's, near the Loangwa river, was taken as a fixed point from which to commence the surveys.

APPROXIMATE HEIGHTS ABOVE SEA-LEVEL BY ANEROID.

	Feet.
Chintankwa ...	4440
Chizimba ...	2890
Chiwali ...	4360
Chaiye ...	2190
Kamela ...	3490
Kaombe ...	5090
Karubuma ...	1990
Katiso ...	2990
Mtinauli ...	4340
Muwundu ...	4290
Mweshia river (upper crossing) ...	2990
Mkwampura ...	4340

HEIGHT BY BOILING-POINT THERMOMETER.*

Kasandwe ...	4795
Kwakumbi ...	1818
Mambesa ...	2173
Sunda ...	2062
Saide ...	1931
Lusuaswe river camp ...	1984
Mzassa ...	1612

ON SEA-BEACHES AND SANDBANKS.†

By VAUGHAN CORNISH, M.Sc. (Vict. Univ.), F.C.S., F.R.G.S.

§ 11. ON THE CHESIL BEACH, A LOCAL STUDY IN THE GRADING OF BEACH SHINGLE.

The Chesil Bank has long been a sort of prize puzzle among beaches, and space forbids detailed reference in this place to the somewhat extensive series of papers which geologists and engineers have written upon the subject. To put the matter shortly, the chief *crux* has been the circumstance that the pebbles are fine at the west end and coarse at the east end. This has been generally regarded as a peculiarity to be explained by special causes, as, *e.g.*—

(*a*) That the material travels from east to west, and not from west to east,

* Kindly communicated by Dr. J. S. Hyland.

† Paper read at the Royal Geographical Society, March 16, 1898. Continued from p. 543.

which is to make the material travel for the greater part of its course against the wind and waves and stronger tide current.*

(*b*) That the material travels from west to east, but that the sea transports the larger stones more quickly than the small.†

This seems to be a mistaken deduction from the circumstance that large pebbles can outstrip smaller ones when rolling freely down a slope, a case which has little analogy with the transport of pebbles along the shore, where buoyancy is the important factor.

(*c*) That the arrangement of the shingle on the Chesil Beach is due in but small part to what is happening now and has happened of recent years, being mainly due to circumstances operating through long preceding periods.

Now, the stones supplied in bygone ages were either friable or they were not.

FIG. 3.—EAST END OF CHESIL BEACH.

If friable, they no longer remain on the surface of the beach; if not friable, then such as still remain on the surface of the beach have made countless journeys to and fro in the course of countless tides and waves. The Chesil Beach is periodically raked over by the sea throughout its whole length and breadth. Thus the present arrangement of the stones upon the surface of the beach is certainly conformable with the present circumstances of wind, wave, and tide, whatever may have been the original mode of supply of the shingle.

The Chesil Beach, in the greatest extension ascribed to it, is reckoned to reach from Bridport harbour to Chesilton In my study of the grading of shingle on this beach, after two preliminary visits to the Chesilton end, I started from Bridport harbour, and made my way on foot from thence to Abbotsbury (first day), taking samples of shingle, and thence on foot and by boat to Chesilton (second day). On

* For particulars of the tides, see King's 'Channel Pilot,' 12th edit.

† Sir John Coode, *Min. Proc. Inst. C.E.*, vol. xii., 1852-3.

the third day I went by boat close under the shore to Blacknor Point, landing occasionally, and then walked back from Chesilton for about a mile westward along the beach. Near the west end of the beach the material of the cliffs is mostly fine, and hence in travelling will be graded up, *i.e.* the *average* size will increase (Law 2). It is, however, obvious, upon slight inspection, that the small shingle of the beach, from Bridport harbour to Burton Bradstock, is not mainly derived from those cliffs, and hence the grading of their detritus is not the principal, and probably is but a small factor of the whole process of grading up of the shingle during west-to-east travel. I found that the increase in size of shingle was very gradual until near the Chesilton end when the increase became rapid, at the same time that a certain kind of flattened white stone became conspicuous. On arriving at "the end of the beach," that is to say, where the foreshore is almost entirely composed

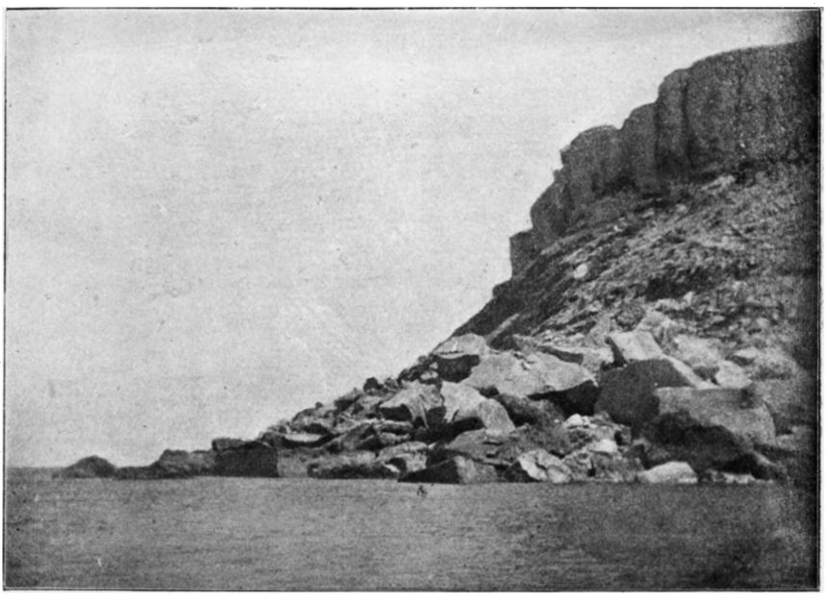

FIG. 4.—BLACKNOR POINT, PORTLAND.

of material freshly supplied from the Portland cliffs, it was evident that these white stones were from the Portland rock, which is here fed to the foreshore by tipping the waste stone of the quarries, which have for many years been extensively worked on the plateau (Figs. 3 and 4). Almost all the fragments thus supplied to the foreshore are large, for not only is the stone compact, but, as is easily recognized, the material is sorted by sizes in the well-known way by tipping, the fine stuff mostly remaining near the top, and the large fragments mostly reaching the bottom. Nevertheless, the material within reach of the breakers, though mostly large, contains a notable quantity of little stones, not, however, rounded shingle, like the small stones near Burton Bradstock, but for the most part angular, which indicates that they have been produced on or near the spot by chipping and breaking of larger stones. Under water I saw, from the boat, a great store of rounded boulders, larger than those upon the beach. On retracing my steps westwards along the beach, I lost sight of the chips almost immediately. My attention was given to the flattened white stones, which I found to decrease rapidly in average size within the first mile of their origin (Law 1). We see, then, that the grinding down and bodily removal of fine stuff from the fresh detritus, copiously supplied by the Isle of Portland, is an important factor in the grading of the beach in its eastern part. The sudden change in the direction of the coast-line at Chesilton is sufficient to account for the supply to the beach of a very large proportion of the big fragments from the quarries and cliffs (for the south-westerly winds must send the waves along the shores of Portland in towards Chesilton). On the other hand, the strong *outset* along this shore (see *post*, Fig. 11) is sufficient to explain a rapid removal of the *chips*.

The wind during my visit being easterly, I saw, especially in the neighbourhood of Abbotsbury, how the gentle waves from the east, which must transport shingle in a westerly direction, were picking out all the smaller stones, so as to leave the part of the beach which they raked over much coarser than the beach immediately beyond their reach. This illustrates how the operation of Law 5 assists to increase the proportion of fine to large shingle at the west end. But on reflection, while the proportions of the things seen were still present in the mind's eye, it seemed to me that something was still lacking to explain the greatness of the accumulation of fine, rounded (and therefore travelled) shingle at the west end, an accumulation the more remarkable that large quantities are annually shipped away at Bridport harbour, and that the shingle there is mostly fine throughout its whole thickness. I therefore took an early opportunity of examining the shore to the westward of Bridport, which, strictly speaking, I ought to have done before, for no beach not supplied by waste of the shore at back of it can be adequately studied within its own limits; we ought always to go beyond and examine its sources of supply from both ends. I started from Lyme Regis and went to Bridport by boat and by walking, taking samples of the shingle, and then worked my way back to Lyme; and here I may note that it is advisable to walk a beach both ways when studying the grading of material. The trend of the coast changes at Charmouth, just eastwards of which the great accumulation of shingle which characterizes the eastern part of Lyme Bay really begins (Fig. 5). On the lonely shore between Charmouth and Eype, *Golden Cap and Thorncombe project somewhat from the line of coast, and a reef of rocks projects from each headland, forming altogether very considerable natural groynes, the last before Portland.* On the western side of Golden Cap is a considerable shingle beach, which rises to a notable height above ordinary tide-level, and is composed, near the promontory, of coarse shingle (Fig. 6). On the east side of the promontory the level of the beach is lower. I commenced taking specimens about the middle of the bay opposite Chidcock (or Seatown) Mouth, and found a steady increase of size eastwards, accompanied by an increase in the height of the beach until the Thorncombe or Down Cliffs double promontory was reached, where the shingle was about as big as that at Chesilton. From this point the beach to Golden Cap presents to the eye an imposing accumulation of shingle. On the east side of the promontory of Thorncombe there is no proper beach accumulation, the sea reaching the cliffs at high tide; but a beach begins to form about opposite Eype Mouth, the material being the finest shingle (Fig. 7). On the east side of Bridport harbour the size of the shingle is already *slightly* greater, and thence eastwards, as we have seen, the increase of size proceeds slowly until we near Portland, when it becomes rapid. It is noteworthy that on the west side of Bridport harbour the shingle under the training wall or pier is bigger, not only than that on the east side, but than that at Abbotsbury. Westwards of Lyme, again, there is no lack of large shingle in favourable situations, as, *e.g.*, at Seaton and at Beer.

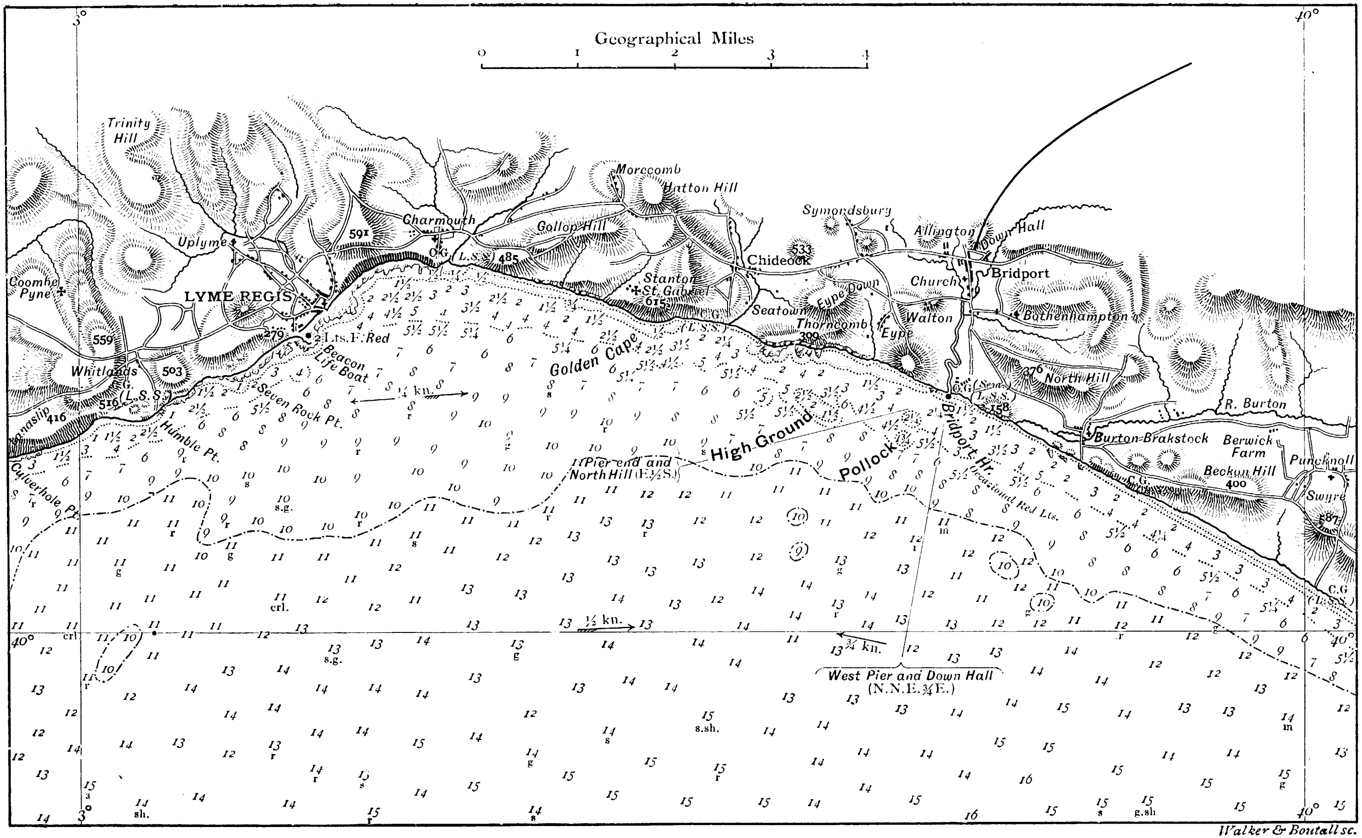

FIG. 5.—CHART: LYME TO BURTON BRADSTOCK.

FIG. 6.—SHINGLE BANK, WEST SIDE OF GOLDEN CAP.
(*From a photograph by F. W. Shephard, Lyme Regis.*)

It appears, therefore, that, in addition to the causes already adduced as contributing to produce the observed grading of the Chesil Beach, the natural groynes at Golden Cap and Thorncombe are of capital importance, for it is these projections, to a far greater extent than the character of the local rock, which determine the supply from the west of an overwhelming proportion of fine material to the western end of the Chesil Beach (see Law 5).

There may be other factors, in addition to those of which I have taken account, contributing to produce the grading of shingle upon the Chesil beach; indeed, it is never permissible to assert that all the factors have been ascertained which contribute to produce any natural phenomenon. But I think the causes I have adduced are adequate to explain the moderate store of facts which we as yet possess as to the sizes of shingle upon different parts of this beach. To recapitulate, the salient points as to grading on the Chesil Beach are briefly as follows:—

1. The beach is fed at both ends (Bridport and Chesilton).

2. The material fed in at the west end is mostly fine, owing chiefly to the natural groynes at Golden Cap and Thorncombe.

3. The material fed in at the east end is mostly coarse, owing to the nature of the local rock and the mode in which it is supplied to the foreshore.

4. The main drift of water is easterly, but

5. Of the fine shingle carried eastward from Bridport, much is brought back by waves from the east; whereas

6. The strong outset at Chesilton removes such fine stuff as may be there supplied from Portland.

7. The largest waves converge on Chesilton from both sides.

It will be noticed that there is nothing abnormal in all this, but that the co-operation of causes is remarkable.

§ 12. The Influence of Specific Gravity on the Behaviour of Beach Material.

(*a*) Dense Minerals.—The angle of slope of the ridge of a shingle beach depends primarily on the materials of which it is chiefly composed, on their size, shape, and specific gravity. *Regimen* is attained when the assistance which gravity gives to transport with the back-wash makes the seaward equal to the shoreward transport. An individual pebble of equal size to those of which the beach is mainly composed, but of twice the specific gravity, if brought on to the *regimen* slope of such a beach will work its way down to the bottom, for its extra resistance to the back-wash is mainly that of greater inertia, whilst it resists the onwash by diminished buoyancy also. Thus it happens that dense minerals are not commonly found upon the *Fulls* of a shingle beach; but, as size diminishes, difference of specific gravity makes less and less difference in buoyancy, hence the dense minerals are ordinary constituents of sandy beaches.

(*b*) Flotsam and Jetsam.—Bodies which have so low a specific gravity that they float in less than their own depth of water are flung in upon the shore by the breaker, riding in on the back of the wave, as boats are beached in a rough sea. As soon as the depth of the water is too small to float them, they are stranded, and this is the perfection of the action by which shingle *Fulls* are formed. These objects are pushed up by each succeeding onwash, in the same way that a boat is hauled up, viz. by partial flotation on the arrival of deeper water. They thus reach the extreme margin of the wash, where they form the wrack which marks the limit of the sea's advance. The wrack is sometimes collected together out at sea. Thus, in Poole bay, when a calm or a light off-shore wind follows rough weather, one occasionally observes that the flotsam which has been drifting widely scattered on

FIG. 7.— THORNCOMBE, FROM EYPE MOUTH.

the fresher waters of the ebbing tide, is caught and collected where the burrowing salt water wedge of the incoming tide rolls up the lighter bay-water as a scroll. The welling up of the water is indicated by a smooth streak,* which stretches for some miles, in appearance a meandering stream, and here the wrack collects. When the water of the incoming tide reaches the shore, the strange collection of oddments is cast upon the beach.

A body drifting in water is set so as to offer the greatest resistance to its passage through the water. Thus, a disc borne by the swirling motion of the incoming wash has its broad face downwards, resisting the upward swirls. This resistance to motion *through* the water gives the disc its greatest buoyancy. When hurried back in the shallow stream of the back-wash, the disc tends to set so as to resist the stream—that is to say, edge downwards. Thus, at the same time that the water has become shallower, the depth required to immerse the disc has become greater. In this way flat shells are stranded on the beach.

The sea's power of transport of detritus depends mainly upon buoyancy. The range of specific gravity of detritus is small compared with the variation of the size of the particles which the sea moves. Therefore the buoyancy of the earthy materials which the sea has to deal with, and hence the power of the sea to transport them, depends mainly on comminution.

§ 13. Sandy Beaches.

(*a*) The Sub-stratum of Shingle.—Sandy beaches are found not only where shingle is wanting, but where the *proportion* of shingle to sand is small. To fix our ideas, we will take the case of the sandy beach between Bournemouth and Poole Haven, on either side of Branksome Chine. The sea here is shallow, and the sea-floor is covered with sand. The cliffs, of about 100 feet, are mainly sandy, with a relatively small proportion of stones. These cliffs (which waste somewhat rapidly by weathering and drainage) must have supplied, even in quite recent times, a quantity of stones sufficient to form a shingle bank, and as the sea seldom reaches the cliff-foot, and there is no platform of hard rock, such a beach would be fairly permanent. Instead, however, of being collected in a bank with sand visible at its foot at low tide, the shingle tends to form a layer underneath the sand of the beach and underneath the sand seawards of the beach. It is only visible when the sand is removed either (1) after a succession of gales, (2) locally by a brook, (3) just behind the breaker, the pumping action of which sorts the material by sizes, increasing the *proportion* of shingle to sand, so that the surface there is often quite stony.

It is important to explain why the shingle derived from the wasting of the cliffs does not follow their recession in such a manner as to form a shingle bank. Something can be done towards providing an explanation by pointing out that stones do not travel readily up on a bed of soft sand, and that the breakers of a flat shore, falling, as they do, on a cushion of water, cannot readily *push* shingle before them, and therefore have to act mainly by the rush of water from the back of the wave. The examination of these disabilities, however, only serves to show that they are quantitatively insufficient to account for the failure of the sea to collect the shingle in a marginal bank. The alteration of the relative positions of sand and shingle from that observed, say, at Eastbourne, Hastings, or Folkestone, is far too great to

* With a light on-shore wind, I have seen the line of meeting of the tidal waters marked, not by a smooth streak, but by a line of foam, where little waves were *breaking*. In this case there are probably two salt-water wedges, with a wedge of the brackish water interposed.

be accounted for by differences in the relative mobility of the individual pebble and the individual sand-grain. *The attempt to deduce the behaviour of a heterogeneous aggregate from the observed behaviour of individuals representative of the constituents is foredoomed to failure, unless allowance be made for the proportion in which they are respectively present*, and much that has been written upon beaches is vitiated by neglect of this rule. Observations of the behaviour of shingle where present in excess lead to erroneous conclusions if applied without correction to the behaviour of disseminated shingle. We must, therefore, once more have recourse to the statistical method. At the foot of our sandy beach we find pebbles exposed under the breaker; why are these not driven up the slope of the beach to the limit of the wash? Because, *when the intensity of action begins to diminish, the pebble is soon buried by the relatively great quantity of sand which is dropped there, and is thus removed from the sphere of action*; for in beaches, as in dunes, it is only the top layer which moves. Thus the shingle which underlies a sandy beach is practically stationary, not for want of mobility, but for lack of opportunity for movement. The sand of the beach comes in and goes out according to the weather* and the seasons, the beach being thickest in summer and thinnest in winter, and occasionally almost stripped of sand after a succession of gales. When the sand is carried out, the shingle is for the most part left behind, necessarily at a low level. The incoming sand buries it, and so prevents the wash from pushing it to a higher level. Thus each round of the seasons tends to leave the fresh supplies of shingle as a bottom layer close to the eroded sea-bed. Thus, if the finer material be present in excess, it smothers the shingle and forms the surface. If the shingle be present in excess, so that pebble beds on pebble, the fine stuff is floated away from the steeply-sloping surface. In either case the material present in great excess normally forms a bank, beneath which the material which is present in small quantity tends to spread out as a layer.

(*b*) The "Low" and "Ball" of a Sandy Shore.—The formation of a beach-ridge, or *Full* of sand, is well seen when the sand is being brought in during off-shore winds. Sand being readily raised by upward-swirling water (which is equivalent to suction dredging), *the building up of a Full of sand in front of the breaker is accompanied by the excavation of a trough, or Low, at the back of the breaker* (Fig. 8). This is roughly similar to the simultaneous excavation and elevation which produces the ridge and furrow so well known as "ripple-mark." Fine dust or mud settles too slowly, coarse shingle too quickly, to lend themselves readily to this mode of distribution by waves. A *Low* is dredged out in sand when the breaker-line remains stationary for a time, as, *e.g.*, during tidal high water. During the ebb of spring tides, a lagoon is often left between the beach and a second stretch of sand. This lagoon marks the strip where the breakers act during the period of neap tides. At low water of spring tides, the belt of sand beyond the *Low* is a sort of beach, the seaward face of which is where the wash of the waves acts. When the tide is up and the sea is rough, there is an outer line of breakers on this bank, which is called the *Ball*.

(*c*) Ridge and Furrow Structure on a Sandy Beach.—A continuous *Full* is formed by on-shore action with gentle waves, but as the size of the breakers

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* In a rough sea, the removal of coarse sand and fine shingle is presumably facilitated by the inertia effect already referred to. The shoreward movement of the wave is so short and sudden that the small stony particles lag behind the water. The seaward swing of the water, on the other hand, lasts long enough to impart its motion to them.

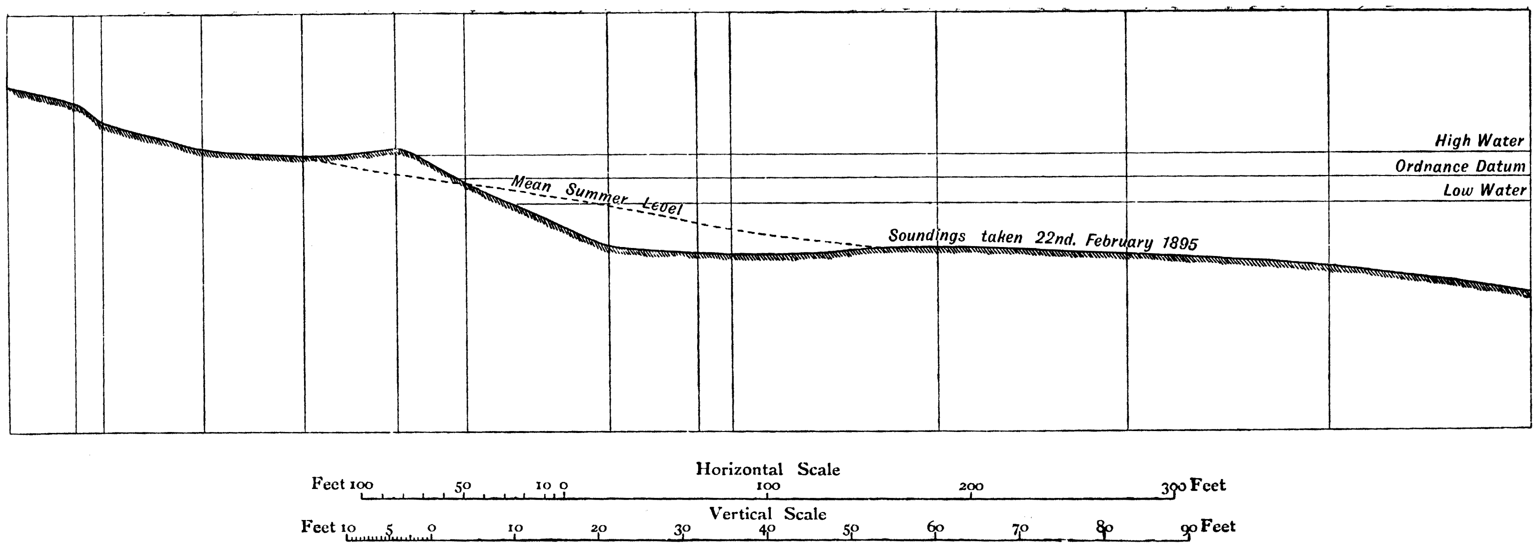

FIG. 8.—SECTION OF SHORE AT ALUM CHINE, BOURNEMOUTH.

increases the wash tends to make the slope less steep. Neither the force nor the resistance are absolutely uniform along the shore, so that this action commences at selected places. From the moment that even the shallowest groove is thus formed, the back-wash finds its way to sea almost entirely by this path. The discharge of the breaker continues, however, to send the on-wash up the ridges as well as up the furrows. Sand, therefore, is still deposited on the ridges, which may continue to increase in height while the absolute level of the troughs may be lowered, and the amplitude from the crest of the ridge to the bottom of the trough necessarily increases. In this way is produced that succession of ridge and furrow *at right angles to the sea-front* which is doubtless familiar to many, from the inconvenience it causes to the pedestrian.

Shingle Barchanes.—A similar structure is often produced when the waves of the receding tide have to deal with a line of shingle uncovered beneath the breaker during the time of high water. The shingle collects in ridges with

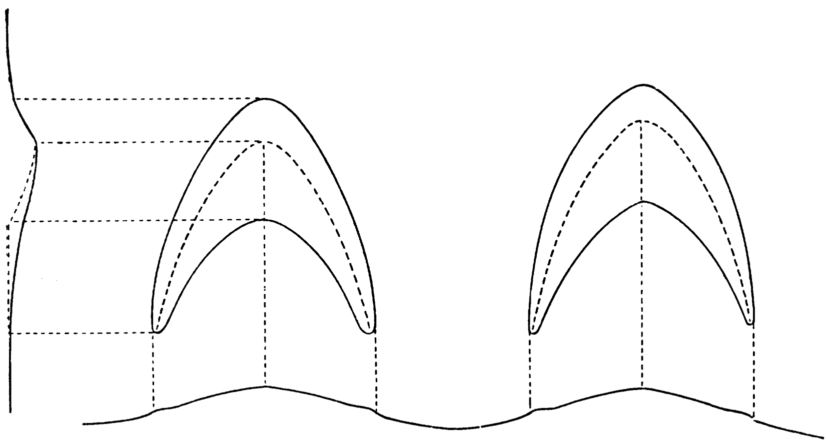

FIG. 9.—SHINGLE *BARCHANES* ON A SANDY BEACH.

intervening troughs of sand, the shingle being only swept out by the back-wash where the water is concentrated in troughs. Fig. 9 shows the form and arrangement of these accumulations of shingle, which may be termed *shingle barchanes* from their shape. Their analogy with the dune called a barchane is obvious, and this renders superfluous any detailed account of how the shape is produced.*

The carving of a sandy beach into ridges and furrows, the axes of which are parallel to the line of action of the wash, alters the character of the *Low.* The sand drawn out down the troughs forms here and there bars across the *Low*, which at low water spring tide is seen cut up into a number of oblong or oval lagoons.

(*d*) THE FLOODING OF A FLAT SANDY COAST.—Although the wash can pile up sand in a *Full* owing to percolation, this action does not afford the same protection against flooding by the sea as does the fulling of shingle. This is not merely due to the greater liability of sand to be swept off-shore, but also to the circumstance that the height reached by the wash is much less when it runs a long course on the nearly flat shore of sand. On such a shore it is easy to observe that the edge of the wash is more and more below the level of the crest of the breaker in proportion

* "Formation of Sand-dunes" (*Geographical Journal*, March, 1897).

as the breakers increase in size. Protection from flooding on a flat sandy shore is given by the blowing of sand into dunes.

§ 14. On the making of Sandbanks and Sandy Forelands.

(*a*) Tidal Nodes.—In tidal seas the *rate of change* of currents is great, which brings out the inertia effects which sand shows so much better than do mud and shingle.

When a body which is capable of transmitting a disturbance, as a pulse, is disturbed at any part, a pulse is transmitted to the boundaries of the body, whence it resurges. The pulsation continues for a time, but ultimately dies out. If the disturbance be repeated at a short interval of time the second pulsation encounters the resurging of the first, and if this repetition of disturbance be kept up at regular intervals, the body presently attains a condition of persistent rhythmical vibration, being parcelled out into vibrating segments, whose boundaries are nodes. The forms of the segments are various, according to the mode of agitation of the body and to the contour of the boundary. The shallow tidal seas are thus parcelled out in vibrating segments bounded by nodes. The following remarks are intended to apply to such areas. Confining our attention to the tidal agitation of the sea, we perceive that no particle of sea-water will wander, but that it will vibrate about a position of equilibrium. The extremities of its excursions are also the extremities of the excursions of particles in the neighbouring vibrating segments. A line drawn through the points of meeting is a node. *The lines of demarcation between vibrating segments are probable positions for the accumulation of sand.** In the vicinity of a nearly straight coast-line the vibrating segments are, I suppose, elongated ellipses, and accumulations may take place along the nodal lines AA′ and BB′ (Fig. 10). If the

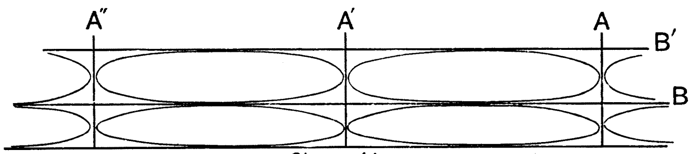

FIG. 10.—TIDAL NODES.

position of the nodes remained absolutely fixed, the greatest accumulation would take place along the A lines (at right angles to the shore), towards which there is the greatest amount of motion. But with the variations of the tides the nodes oscillate about a mean position; if, therefore, the motion in the vibrating segments be violent, there is at intervals violent tidal agitation at the mean position of the A nodes, and, unless the supply of sand be very great, accumulation does not take place there.

The displacements of the B nodes, on the other hand, are less violent, and it is therefore along these lines that the principal accumulations take place when accumulation is prevented at the A nodes. Thus I conclude are formed—

(*b*) Longitudinal Sandbanks.—Such are the sandbanks parallel to the shore which are numerous off the coasts from Flamboro' Head to the South Foreland, and from Calais, at least, as far as the Zuyder Zee. These sandbanks are parallel to the main run of the along-shore tidal currents. They present analogies with the longitudinal dunes of deserts. When the formation of such shoals is once

* Compare Faraday on "Acoustic Figures" (*Phil. Trans.*, 1831).

started, the mechanism which produced them is thereby assisted, for the currents are deflected by the ridges and concentrated in the intervening furrows. Any sand deposited at slack water in the furrows is thus swept out, say by the flood-tide, and carried as far as the end of the ridge. Here are formed two eddies of water close to one another. The sand, being denser than the water, eddies in wider curves, and the sand brought by one eddy is thus flung into the other, whose motion is equal and opposite. Thus the sand is concentrated along the prolongation of the axis of the shoal near the inner margin of the two eddies. The same kind of action lengthens the shoal at the other end during the ebbing tide. Such shoals, when small, are liable to shift with those irregularities of the vibratory motions of the sea which result from seasonal and casual variations of weather. The larger shoals are not subject to much movement from short-lived disturbances, even if violent, for these large heaps of incoherent material cannot be moved bodily, but only by the rolling of the surface layers. On the other hand, a very small disturbance of conditions, if long continued, can shift the largest shoal. Such a disturbance is the recession of the coast-line. It is probable, *e.g.*, that the shoals off the coasts of our eastern counties tend to travel at the same rate as the coast is cut back.

(*c*) THE VERTICAL SECTION OF SANDBANKS.—Sandbanks frequently rise steeply, their material standing at the maximum resting angle. These steep sides are more common than in the case of dunes, for winds of maximum force are comparatively rare, and dunes are usually seen with the shapes imparted by gentler winds. In the case of tides, on the other hand, slack water, during which a large proportion of the deposition must take place, lasts a comparatively short time, and the shoal is shaped by the scouring currents which succeed.

There is another action besides scouring which gives steep sides to sandbanks, especially those which rise from fairly deep water. The action of the waves being in such cases great at the surface of the shoal and small at the base, sand is continually shaken over the edges, and, falling into nearly still water, gives the well-known steep *talus*. The rapid ratio in which the intensity of wave-action increases with approach to the surface thus tends to preserve a flat top to shoals. The hills and hollows of the surface of such a shoal as the Dogger bank are much less marked than is common in the case of a tract of dunes in deserts of deep sand, for the force of wind increases in a relatively small ratio with increase of elevation.

(*d*) BANNER SANDBANKS.—The sandbanks which accumulate on the more sheltered side of headlands, good examples of which are the Skerries shoal, eastward of Start Point, and the Shambles shoal, eastward of Portland Bill, suggest by their shape and position that they are deposited in "the eddy" caused by the headland (Fig. 11). This mode of statement, though perhaps not altogether incorrect, is apt to mislead. Thus, when the tide is running up-channel, there is an eddy known to the navigators of small vessels on the east side of Portland. Not only is the area of the obvious eddy very small compared with the area of the Shambles shoal, but its centre is not even situated within that area, but quite close under the Bill. As a matter of fact, *the materials (broken shells, etc.) which form the Shambles sandbank are not deposited in still water*, as is clearly brought out in the following note printed upon the Admiralty Chart 2450 (Portland to Owers). "From about II.^{hrs} to XI.^{hrs} F. and C. there is an outset from the west bay of Portland of nearly 9 hours' duration, which closely skirts the rocky shore, and gradually increases in strength as it approaches the Bill. It rushes past the Bill and over the Portland Ledge at the rate of 6 or 7 knots at springs. A short distance eastwards of the Ledge this outset is met in the latter half of its course *at nearly right angles* by the stream which sets for nearly 9½ hours (viz. from VI.hrs 20m to III.hrs 50m F. and C.) out of the east bay of Portland; these united streams press on towards the Shambles, which they cross obliquely about E. by N. at the rate of from 3 to 4 knots. The tidal streams set over the Shambles in an easterly, northerly, and westerly direction, making to the eastward at III.hrs 45m, and to the westward at X.hrs 45m, and attaining a rate of 3 to 4 knots." Thus *the sand deposits from the mixing waters of the meeting streams*, an effect that is not surprising when we consider that the mixing of waters is achieved by vortices.

The surface layers of this shoal are frequently in active motion even in calm weather,* and the permanence of the shoal under these conditions has excited surprise. In point of fact, *the permanence of a sandbank is ensured by equality of supply and loss*, the equilibrium being dynamic. As in the case of a banner cloud or a standing

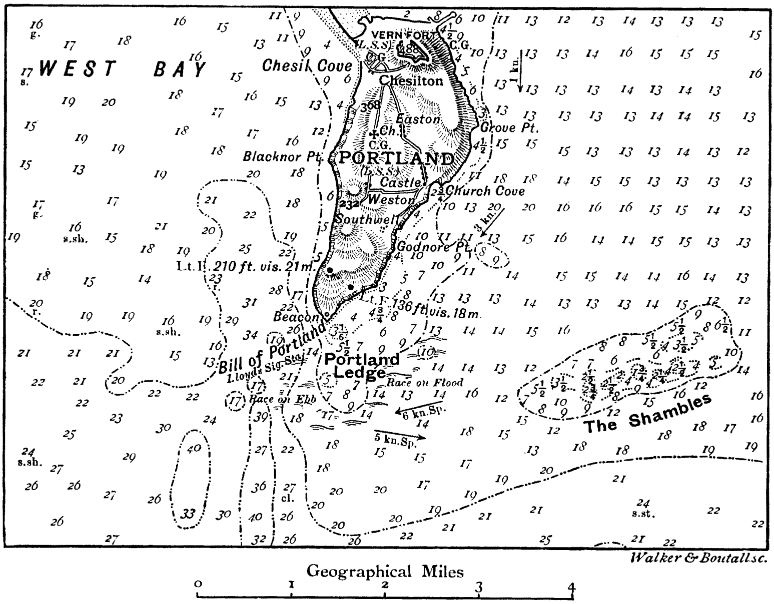

FIG. 11.—CHART: THE SHAMBLES SHOAL.

wave, the structure persists, whilst the material is changed. In the case we are considering, the supply may be reckoned as constant; the loss depends upon the amount of surface. Consequently, if a part of the shoal were removed by artificial means, supply would be greater than loss, and presumably the shoal would grow again to its maximum dimensions. Only the surface particles of a sandbank or sand-hill are removed by currents, so that the material of the interior of a stationary sandbank is unchanged. In the case of a travelling accumulation of sand, such as the moving sand-dunes of the desert, each part in succession is brought to the surface, and the materials may be completely changed.

The position of the Shambles shoal may be considered to be fixed relatively to the Bill of Portland. As the Bill is cut back, so will the shoal shift. When the coast of Portland corresponded with the position of, say, the present 5-fathom line,

* Deane, in *Min. Proc. Inst. C.E.*, vol. xi. p. 217.

the centre of the Shambles was presumably a little south and east of its present position.

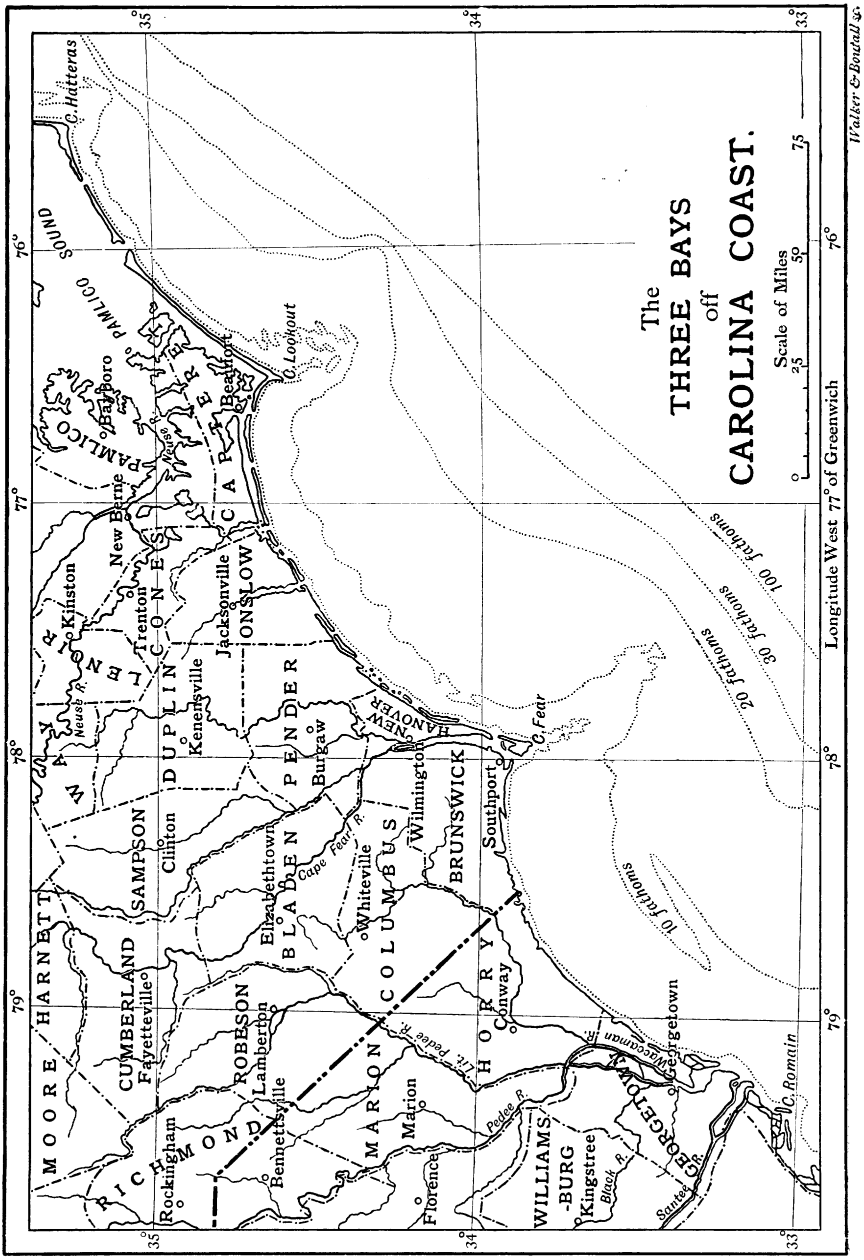

FIG. 12.—CAPES HATTERAS, LOOKOUT, AND FEAR.

(*e*) River Bars.—The entry of the salt-water wedge (see § 2) is probably an important factor in the formation of the sandy bar which usually occurs near the mouth of a river. The inertia of the sand and its superior density must cause it to cut through the stream-lines of the river-water when this is deflected upwards,* so that the sand passes into the salt-water wedge more rapidly and completely than would be achieved merely by settling. But the checking and deflection of the streams is probably not nearly the whole of the mechanism by which the deposition of sand is brought about where a river meets the sea. A great part of this effect is probably due to the motions which attend the mixing of waters, a process which appears to be almost as potent a factor in the formation of sandbanks as is the mixing of airs in the production of clouds.

(*f*) Sandy Forelands and Transverse Shoals.—The accumulation of sand in transverse bars (*i.e.* along what we have termed the A nodes) is the action which

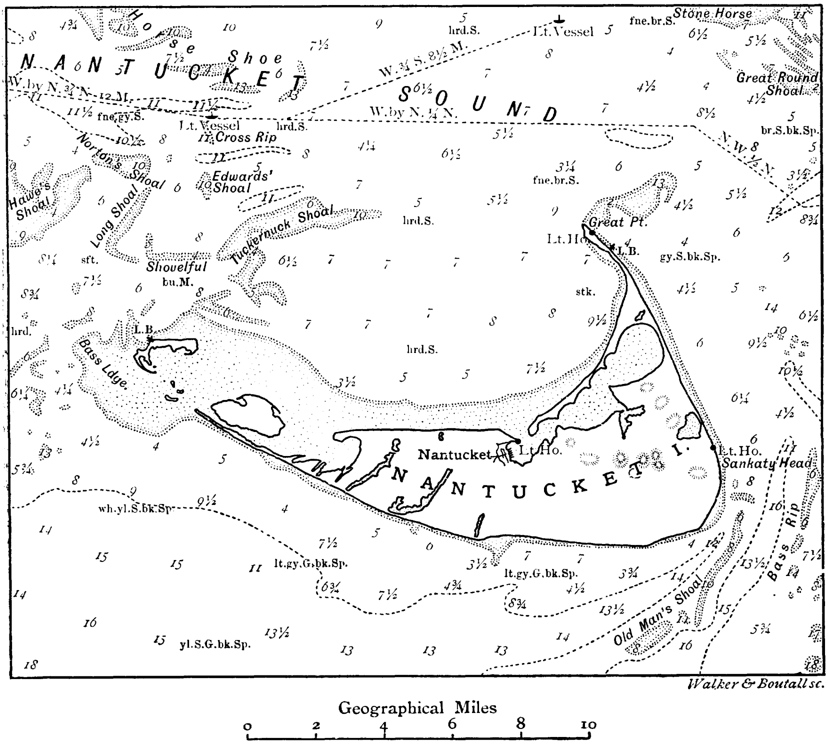

FIG. 13.—NANTUCKET ISLAND.

on a small scale is termed "rippling." It promotes the formation of sandy forelands, for the formation of such a ridge is most readily started with the beach as a base. This fact is to be connected with the circumstance that water is thrown off in eddying masses from the bank of a stream, and the same action must take place when the tide runs along a coast. Evidently this increases the amount of deposit at the coastal extremity of the nodal line. The well-known sandy forelands of North Carolina (Capes Hatteras, Lookout, and Fear) are each continued under-water as spits of sand projecting seawards for miles (Fig. 12). The under-water

* See Humphreys and Abbott, 'Report upon the Physics and Hydraulics of the Mississipi River.'

part of these great sand-ridges is moulded in accordance with the tides and currents of this part of the sea, whereas the contour-line which is "the shape of the foreland," is moulded by the action of the breakers and their wash, which, for this open coast, is equivalent to the local action of the wind, which is stated to be most powerful from the north and east.* In many cases the shape of a sandy foreland, that is to say, the form of the sea-level contour-line, conveys an utterly false idea as to the shape of the sand-hill whose top is the foreland. Fig. 13 shows how the coast-line of the northern spit of Nantucket Island curves away from the weather side, while the submerged part points seaward, presumably under the influence of a current which is stated (Captain Davies, quoted by J. D. Dana, *Man. Geol.*, p. 681 of 3rd edit.) to set from west to east and from south to north. It appears, therefore, that, if the sand which accumulates off the coast of

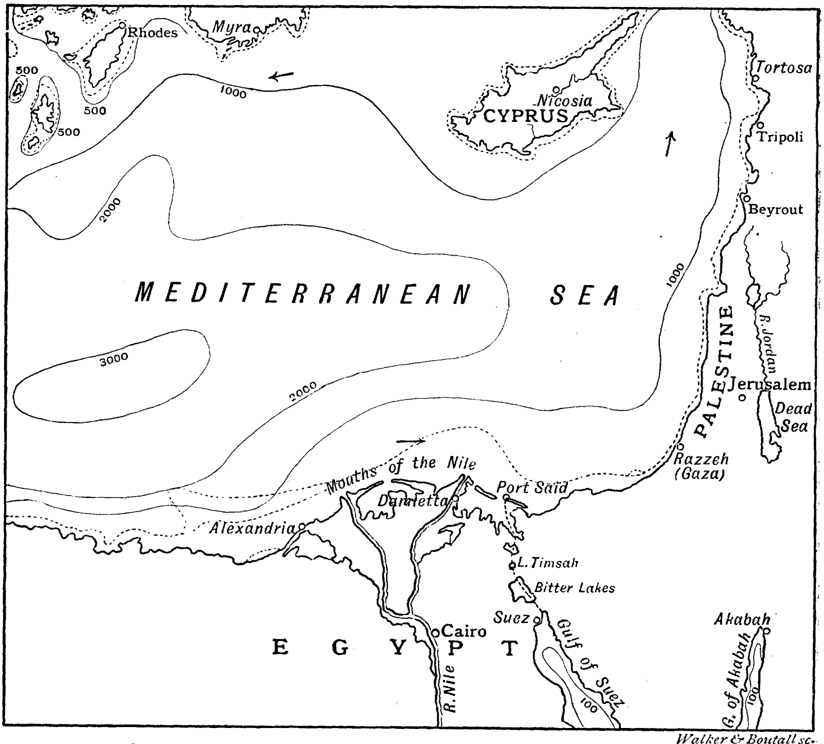

FIG. 14.—DELTA AND SUBMARINE DELTA OF THE NILE (AFTER DELESSE).

North Carolina were really moulded to the curves of contiguous "back-set" eddies induced by the Gulf Stream,† the result of such moulding should be sought, not in the contour of the forelands, where Dr. Gulliver seeks it, but in that of the submerged spits. These spits, however, do not show the required sharp points and

* See Wheeler in *Min. Proc. Inst. C.E.*, vol. cxxv., 1895–96, pt. iii. p. 17, quoting L. N. Haupt; and N. S. Shaler, 'U.S. Geol. Survey, Thirteenth An. Report,' 1891–92, pt. ii. "Geology" (on "The Geological History of Harbours"), p. 128.

† See F. P. Gulliver on "Cuspate Forelands" (*Bull Geol. Soc. of America*, vol. 7, pp. 399–422).

double-concave curves. In the same way, the east-flowing current off the south coast of the Mediterranean is recorded in the form of the submarine parts of the Nile delta (Fig. 14).

A stream which erodes an alluvial channel continually increases its sinuosity (until a "cut-off" takes place), because the opposite banks or shores are close, and the current is relatively rapid. Thus the chief scour is directed into the bays, and deposition on the headlands of the material thus removed is promoted.* Such co-operation does not occur between opposing coasts of the sea, so that the scour is greatest on the headlands, and the tendency is to deposit in the bays material thus eroded.

When a shore is growing by means of the along-shore distribution of detritus brought down by rivers (*e.g.* the coast of North Carolina), the coast-line becomes indented by the growth of sandy forelands, as explained in the last section. The indentation proceeds until the loss of material from the lengthened coast-line is equal to the supply. Now, the forelands grow where the supply is greatest, but as they are built out, the exposure, and consequently the rate of removal at the point, increases. At length, therefore, the indentation of the coast reaches a maximum. If subsequent scouring of the points and accumulation in the bays should shorten the coast-line, deposition would then be once more in excess of removal, and the forelands would be renewed.

The curves of a coast-line, so far as they are due to erosion and deposition, record the *relative* rates of recession (or advance) in different parts. Thus, where a foreland has grown out more rapidly than it has broadened (*e.g.* where rippling action deposits sand off the point below low-water mark, as in the cuspate forelands of Carolina), the curves of the coast are concave to the sea, and the foreland is sharply pointed at their intersection (Fig. 15, A). When the scour off the point begins to

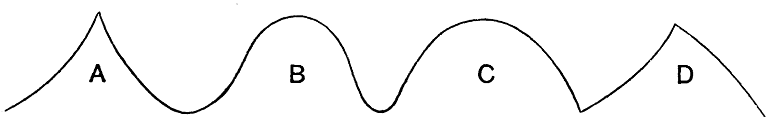

FIG. 15.—COASTAL CURVES.

tell, the foreland is blunted, and the curve of the coast has an inflection (B). When the rate of seaward growth steadily diminishes with increase of size, as is likely to occur when a delta is built out by a river, the curve is everywhere convex to the sea-front (C). When one side of the foreland is more exposed than the other (D), it is common to have the curve C on the exposed side, and the curve A on the sheltered side, as at Dungeness. In this instance the whole form shifts bodily to the left in sympathy with the progressive deflection of the mouth of the Rother (see *ante*, § 9).

(*g*) MANGROVE COASTS.—The growth of deltas and forelands of sand and silt is facilitated where the mangrove and courida grow. The latter, according to Mr. J. Rodway, is the more effective in building out the shore.† In the first place, the roots direct the water into many devious channels, greatly increasing friction, and causing streams following opposite courses to meet and still each other. In the second place, *by yielding and recovering in the moving fluid, not rhythmically but*

* See James Thompson on "The Windings of Rivers in Alluvial Plains" (*Proc. Roy. Soc.*, 1876, p. 5, and 1877, p. 356).

† 'In the Guiana Forest,' 2nd edit.

confusedly, the vegetation produces tumultuous stirring of the waters, which is eminently favourable to the deposition of sand. In a somewhat similar way, waving reeds and grass stop sand driven by the wind. Planting has succeeded best as a means of stopping the encroachment of blown sand, and our sandy coasts might be similarly protected against sea-attack by sturdy plants with matted or tangled structure, and the habit to withstand salt water at their roots. Such growths appear to be at present unknown much beyond the tropics; nevertheless, this mode of protection from sea-attack might afford scope for interesting experiment in colder climates.

In the fascine dam, withies, and the like, by their yielding and subsequent recovery, reproduce one of the features of protection by a natural wall of matted mangrove or courida.

POSTSCRIPT.

The next paper which I hope to lay before the Society will be upon undulating Waves, a subject upon which I have been engaged for some time past. I endeavour to deal with waves of the sea, of lakes, and rivers; with ripple mark and ripple drift and snow ripples; with gusts of wind, and undulating air-waves and their accompanying cloud forms, with the ridging of hillsides, and with such other rock (and ice) structures as are dynamically related to undulating waves.

I shall be grateful for any help which gentlemen interested in these matters may be kind enough to afford me, particularly—

(1) By suggesting problems for investigation.
(2) By assistance in mathematical treatment.
(3) By the loan of, or reference to, photographs and other illustrations.

Before the reading of the paper, the President said: Mr. Cornish gave us a very interesting paper last year on the formation of sand-dunes, which was followed by an admirable discussion, and I feel sure that the paper he is going to read to us this afternoon will be equally interesting. I will now ask Mr. Cornish to read his paper.

After the reading of the paper, the following discussion took place:—

Dr. BLANFORD: I am afraid I cannot contribute anything of value to the discussion. It is very difficult indeed to discuss papers of this sort, which require a great deal of reading and thinking over before any one can form a judgment upon them. Of course, this paper consists partly of facts, some of which are patent to any one who looks for them, and some are less obvious, and partly of conclusions formed by the observer, and it is not fair to attempt to criticize his views without going very carefully into them. I can only say they are exceedingly interesting, and I am only too happy on this occasion, as on a former one, to bear witness to the interest of the paper.

Mr. A. STRAHAN: England is not very large, and if it were not for its shingle beaches, it would be undoubtedly a great deal smaller. They are the best protection to our shores that we can have, and the subject is therefore of much importance from a national point of view as well as a scientific problem. The application of Mr. Cornish's views to a particular example is of great interest. The example I know best is the Chesil Beach, and it would be difficult to find a better specimen of a graded shingle bank. Mr. Cornish, I hope, will forgive me when I say that I do not entirely agree with him, or perhaps I should express myself more correctly if I say that I think he has not exhausted the subject. There is a copious literature on the Chesil Beach, beginning with a paper by Sir John Coode, and including a very fine piece of work by the late Sir Joseph Prestwich. There are great